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Innovation in STEM-Based Learning Projects by Utilizing Ocean Wave Theory as a Source of Electrical Energy Using a Four-Pendulum Pontoon

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Abstract
This study aims to examine the potential of using ocean wave energy as a source of electrical energy through a pontoon system with four pendulums as an innovation in STEM-based learning projects. The method used is a literature review with a descriptive-analytical approach, namely examining various relevant scientific publications related to the design, working principles, and energy conversion efficiency of ocean wave power generation technology. The stages of this research consist of identifying the research topic, conducting a review of scientific sources, examining the design and operational principles of the system, analyzing the collected information, and formulating conclusions along with recommendations. The results of the study show that a pontoon with four pendulums equipped with a Double Free Wheel Rotation Transmission System and a flywheel is able to convert ocean wave motion into electrical energy through a mechanism of converting mechanical energy into electrical energy using a slow-rotating three-phase generator. This system utilizes the swing of the pendulum due to the movement of the pontoon by ocean waves, which is then converted into a rotational motion with high torque to drive the generator. Literature analysis also shows that the stability of the pontoon, the configuration of the pendulums, and the transmission design significantly affect the efficiency of electrical output. Although it has great potential for application in coastal areas and remote islands, further research is needed to optimize the design, improve energy conversion efficiency, and assess its technical and economic feasibility. The findings of this study have implications for strengthening renewable energy literacy within STEM-based learning, while also contributing to raising students' awareness of environmentally friendly energy utilization. The innovation of the four-pendulum pontoon has the potential to serve as a contextual learning medium that supports the mastery of physics concepts and the development of 21st-century skills. The recommendation of this research is the development of a laboratory- or field-scale prototype and its integration into the science curriculum, enabling students to connect theoretical knowledge with real-world applications of renewable energy.

Keywords: *Sea waves, Pontoon, Pendulum, Electrical Energy, STEM*

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INTRODUCTION

Global electricity demand continues to increase along with the development of human civilization and population growth. Currently, most electricity supplies still rely on the combustion of limited and non-renewable fossil fuels, thus creating environmental and sustainability issues. Indonesia, as the world's largest archipelagic country with an area of 1.9 million km² and a coastline of approximately 81,290 km, has great potential to develop renewable energy from the ocean, particularly wave energy (Ribal et al., 2020). Previous studies have shown that the southern regions of Java , Bali, and Nusa Tenggara have an average wave energy potential above 30 kW/m during the easterly monsoon season (Ribal et al., 2020; Waskito et al., 2023). GIS-based analysis also found technical potential reaching ±4.35 GW in southern Malang waters (Setyawan et al., 2023), while technology such as the Oscillating Water Column (OWC) is capable of producing 3.9–5.6 MWh/year in Baron Beach, Yogyakarta (Kurniawan et al., 2022). Indonesia is a large maritime country, which has a great opportunity to develop energy sources from the sea. Almost 2/3 of Indonesia's territory is ocean. Indonesia as an archipelagic country with an area of 1,904,556 km2 consisting of 17,508 islands, 5.8 million km2 of ocean and 81,290 million km long beach, then the energy potential of the sea, especially waves of the sea, has great potential very to be empowered as an alternative primary energy, new and updated, especially for generator power electricity (Yona et al., 2017). One of the ocean parameters or adequate hydrooceanography significantly developed into energy electricity is sea waves. Ocean waves are a new and renewable energy source with economic value, as well as being environmentally friendly because they produce no pollution and are readily available in coastal areas (Milansi , 2023; Arridina & Ibrahim, 2020)

Although various studies have mapped wave energy potential in various locations in Indonesia (Anggraini and Santoso, 2023; Alamsah et al., 2025; Arisanti et al., 2025), several gaps remain that need to be addressed. First, most research is local in nature and has not integrated comprehensive spatial-temporal analysis across all potential areas. Second, economic feasibility analyses, such as Levelized Cost of Energy (LCOE), are rarely conducted, despite being crucial for assessing the economics of implementing Wave Energy Converter (WEC) technology in Indonesia (Waskito et al., 2023). Third, research links with energy needs in remote areas are still limited, thus under-utilizing the potential of wave energy to support local energy independence.

See condition mentioned above in accordance with the topography of the Republic of Indonesia, then Indonesia needs to take a role in research, testing and development of energy from sea. This is because Indonesia is an archipelagic country with thousands of islands or better known as maritime countries, so lots of remote areas / regions that require special handling, including providing power / energy electricity. Beside that reduce dependency will these technologies, towards other countries (Satriawan & Rosmiati , 2022). In addition to technical aspects, the educational dimension is also crucial to consider. Research has shown that students' creative thinking abilities in understanding environmental issues, such as climate change, remain relatively low (Susanti & Lestari, 2023; Agustinaningrum et al., 2024). Therefore, there is a need for STEM-based learning innovations that can effectively connect the concepts of renewable energy with the development of higher-order thinking skills. Based on these conditions, this study aims to identify and analyze the potential use of ocean wave energy as a source of electrical energy as an innovation in STEM-based learning projects. The STEM (Science, Technology, Engineering, and Mathematics) approach has strong relevance in the development of ocean wave energy utilization technology because it involves scientific studies, design engineering, technology application, and mathematical analysis in a unified process (Nazhifah et al., 2023). The development of renewable energy-based learning media, such as Mini Sopetric, has been proven effective in helping students understand the concept of alternative energy (Lestari & Sucahyo, 2023; Sasmi et al., 2025). From the science aspect, this research integrates the principles of ocean wave physics and fluid dynamics to understand the mechanism of energy conversion (Kelley & Knowles, 2016). The technological and engineering aspects are reflected through the design of the four pendulums pontoon system, the selection of energy conversion components, and the optimization of the transmission mechanism performance. Meanwhile, mathematics plays an important role in power calculation, measurement data analysis, and system performance modeling based on ocean wave parameters.

METHOD

The research method used in this study is a literature review focused on theoretical studies and critical analysis of wave energy utilization using a pontoon system with four pendulums (Nuryadi et al, 2023). The research approach is descriptive-analytical, presenting the design concept and operating principles of the system based on previous research results, then analyzing these to identify potential, limitations, and opportunities for technology optimization.

The research procedure begins with determining the study's focus, followed by a search for scientific references from books, journal articles, technical reports, and relevant publications discussing wave power generation technology, pontoon design, and pendulum mechanisms. The references reviewed in this study were selected based on the following criteria: (1) relevance to the topics of ocean wave energy, pontoon design, and pendulum mechanisms; (2) origin from credible scientific publications such as reputable journals, conference proceedings, dissertations, and textbooks published by academic publishers; (3) publication within the last ten years to ensure the novelty of information, except for classical literature considered fundamental; and (4) direct relevance to aspects of physics, technological engineering, and the implementation of STEM in education. The information obtained is then analyzed to formulate a comprehensive overview of the system's design, performance, and implementation challenges in the field.

The research procedures used are as Figure 1.

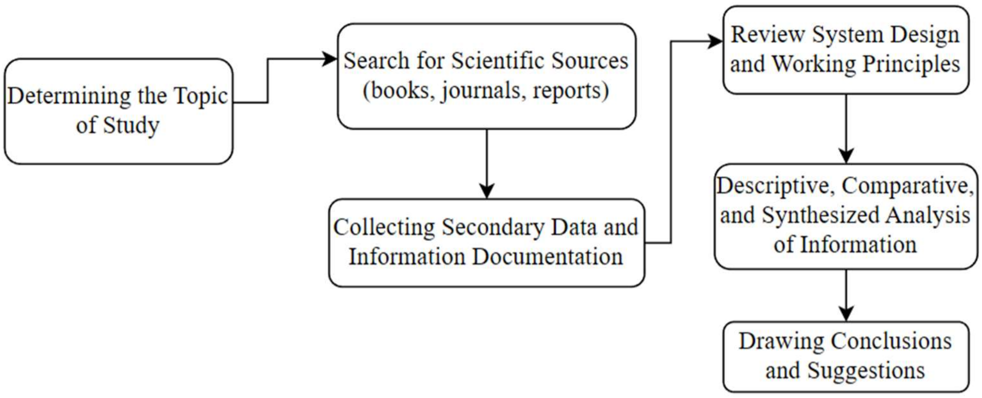

Figure 1. Flowchart of Research Procedures

The data sources used are entirely secondary data sourced from scientific publications, reference books, and previous research reports relevant to the topic. Data collection techniques are conducted through a literature review with a systematic search of reliable sources, complemented by documentation techniques to record technical specifications, design parameters, and key findings from previous research. Data analysis was conducted descriptively to present the results of previous research in a structured manner, comparatively to compare various designs and mechanisms of ocean wave energy conversion, and synthesized information to integrate these findings into a comprehensive conclusion (Syarief et al., 2020). With this approach, the research is expected to provide a conceptual contribution to the development of pontoon technology with four pendulums as an effective and sustainable alternative for renewable energy-based power generation.

RESULTS AND DISCUSSION

The design of this ocean wave power plant consists of four pendulums suspended from steel arms on a pontoon equipped with four floats. The pontoon itself is a ship that is generally shaped like a large box and floats on the surface of the water (Hantoro et al., 2022). The choice of a pontoon-shaped ship as the platform provides stability and buoyancy, ensuring that the system can withstand the forces of the ocean waves while remaining afloat (Prasetya et al., 2024). Additionally, the box-like shape could offer ample space for housing the necessary equipment and components for energy conversion. This tool is equipped with a double free wheel rotation transmission system, fly wheel and generator or dynamo.

The function of these components is to generate the electrical power that has been generated. Double free wheel rotation transmission system likely consists of gears or a similar mechanism that allows the pendulum's rotational motion to be transmitted efficiently to other components of the generator system. The "double free wheel" aspect suggests that the system may be designed to allow motion in both directions, ensuring that energy can be captured regardless of the pendulum's swing direction (Chand et al,. 2025). The flywheel serves as a mechanical energy storage device. It smooths out fluctuations in the rotational speed of the pendulums, storing excess energy during periods of high motion and releasing it during slower periods. This helps stabilize the rotational motion and ensures a consistent output from the generator (Liu et al., 2022).

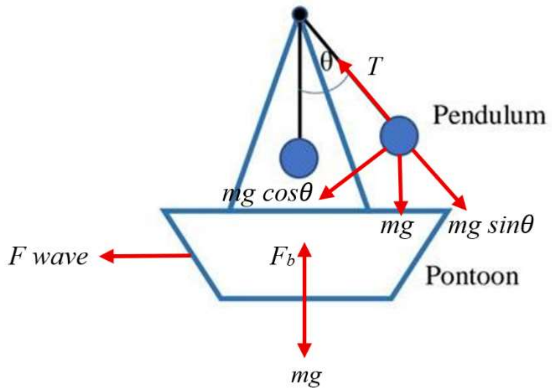

Figure 2. Sketch of An Electric Drive Pendulum System

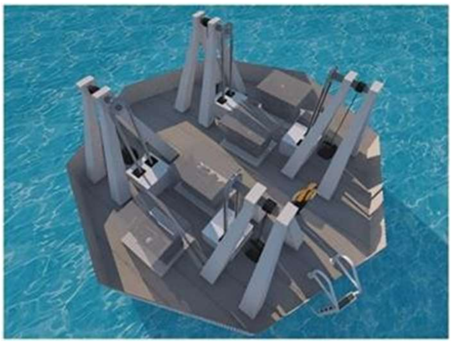

Figure 3. A Device for Generating Sea Wave Electricity from A Pendulum

The working system of this tool begins when the pontoon moves and sways due to sea waves. The pontoon's movement will make the pendulum swing and allow the axis of the two pendulum arms to move and rotate back and forth (Graves & Zhu, 2022). The swinging motion of the pendulum is driven by the kinetic energy of the waves. The back and forth movement of the pendulum will be converted into rotational motion through a mechanism. The resulting rotation will of course be slow but will have a large Torque Moment. By using a Double Free Wheel Rotation Transmission System (DFWRT System) and Fly Wheel, the rotation is increasing the speed of rotation while maintaining the torque to reach the working rotation of the generator/dynamo (Avalos et al., 2022). The generator component is tasked with converting mechanical energy from pendulum motion into electrical energy. Generators and dynamos use electromagnetic induction to generate electricity as they rotate. Sea waves are influenced by wind. Strong winds will make big waves too. The bigger the water waves that are formed, the bigger the electrical energy produced. High water waves when they hit the pontoon will make the swing angle of the pendulum θ tilt or become larger, so that the resulting mechanical force will also be large (Zhao et al., 2025). The electrical energy that has been produced is then distributed via Medium Voltage Air Lines or Medium Voltage Air Lines (SUTM and SKTM). Electrical energy is reduced in voltage through a transformer at the Distribution Substation or Distribution Substation (GADIS). Electrical energy is distributed via Low Voltage Air Lines (SUTR and SKTR) from a distribution transformer with a voltage of 220 volts to the houses of local residents.

The working process of this system is represented in the following Figure 4.

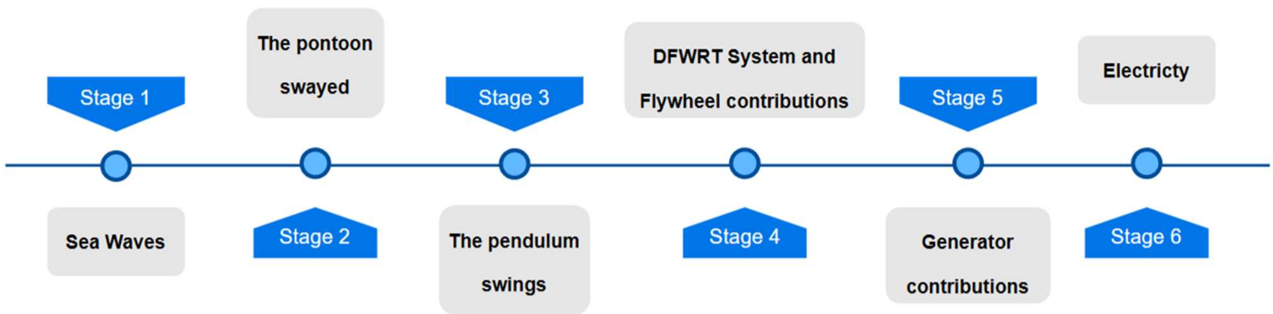

Figure 4. Working Process

In the wind farm building experiment, there is one important part called the pontoon that provides stability and buoyancy (because it is equipped with four floats), ensuring that the system can withstand the force of ocean waves while remaining afloat (Peng et al., 2021). In addition, its octagonal shape can provide enough space to house the equipment and components required for energy conversion. It is equipped with a dual free-wheel rotational transmission system, fly wheel and generator or dynamo. Any movement of seawater will shake the pendulum, moving the double-freewheel to rotate the dynamo to generate electricity (Aminuddin et al., 2020). In this case, a 3-phase AC slow rotation type generator with a maximum power of 500 Watts at 1400 rpm is used. The AC current generated is then converted into DC current using an adapter to charge or charge the battery. The current stored in the battery or batteries is then converted back to 220 volts AC using an inverter.

From the ground trials, when the pontoon was manually shaken, the resulting rotation was about 90 rpm. Measurements showed a current of about 1.2 to 1.6 Amperes with a voltage between 18 to 24 Volts. The formula used to calculate power is:

$$P = V \times I \tag{1}$$

Description:
P = Power (watts)
V = Voltage (volts)
I = Strong electric current (amperes).
So, from this formulation, the average power is obtained:

$$1.3 \text{ A } \times 24 \text{ Volts} = 31,.2 \text{ watts}$$

From the manual test, it is expected that during the direct test at sea, the pendulum swing due to large sea waves can make the Ө angle value even greater. So that the mechanical force generated will also be greater. The force F obtained from the pendulum swing is converted into electrical energy. The alternating motion of the pendulum will be transformed into rotary motion through a mechanism. The resulting rotation certainly has a large torque moment, using a transmission system and flywheel or flywheel the rotation is raised to the working rotation of the generator/dynamo so that the generator/dynamo will produce the expected electrical energy (Wan et al., 2022).

Choosing the right number of pendulums is an effort so that the pendulum can move and rotate stably and maximally. If only 1-2 pendulums are used, the pendulum movement will be limited to a maximum of ½ rotation (maximum angle of 90º). Therefore, this experiment uses 4 pendulums so that the four pendulums can move optimally.

In this study, the pontoon model data used includes, mass 11038.79 kg, volume 39.07 m3, surface area 108.42 m2, and center of mass (0, 0, 0.30). The fluid model is Multi-fluid (fluid-1 is under fluid-2). Fluid-1 with dynamic viscosity 0.00104362 Pa.s, and Density 998.4 kg/m3. Fluid-2 with dynamic viscosity 1.85e-05 Pa.s, and density 1.2 kg/m3. The flow model used is laminar, with a gravity intensity of -9.81 m/s2, reference length of 3 meters, and reference velocity of 1 m/s.

The graph of the pontoon motions on the y-axis (pitch) at a wave height of 0.5 -1.5 meters is represented in Figure 5.

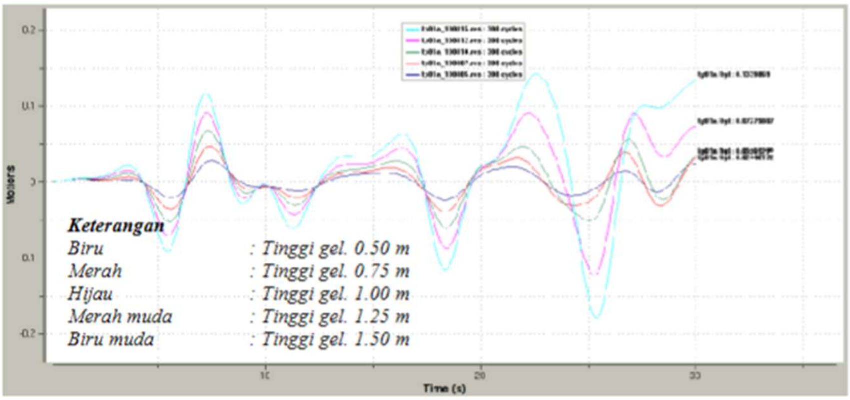

Figure 5. Graph of Pontoon Motion Against the Y-Axis

From the experimental data, the maximum motion value of the pontoon on the y-axis (pitch) was obtained at a wave height of 0.5 - 1.5 meters. The lowest value is 1.64° at a wave height of 0.5 meters. The highest value is 10.28° at a wave height of 1.5 meters. Therefore, as the sea waves rise, the pendulum elevation angle (Θ) will increase. So that the rotation in minutes of the pendulum (rpm) will be greater. The voltage obtained from the dynamo conversion produces an electric current that will be channelled to the electrical substations.

The graph of the moments of the pontoon on the y-axis at a wave height of 0.5 - 1.5 meters is represented in Figure 6.

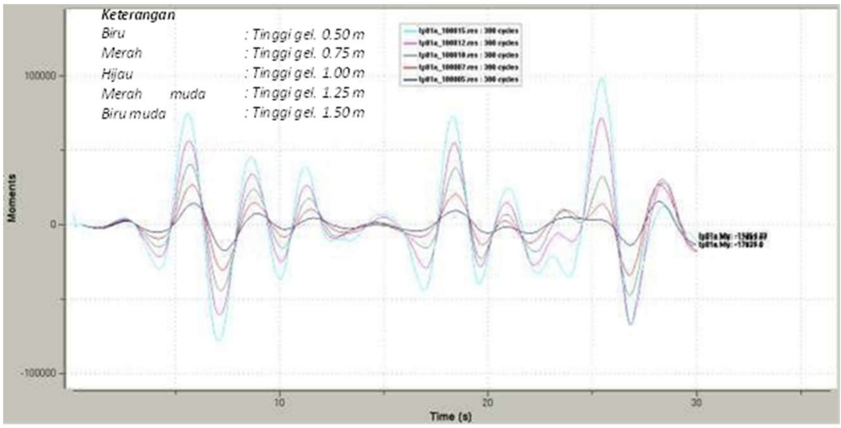

Figure 6. Graph of Pontoon Moments Against the Y-Axis

From the experimental data, the maximum moment value of the pontoon on the y-axis is obtained at a wave height of 0.5-1.5 meters. The lowest value is 17058.09 Nm at a wave height of 0.5 meters. The highest value is 98236.23 Nm at a wave height of 1.5 meters. Pontoon moments can be both moments of inertia and moments of force which can facilitate the design and analysis of pontoon structures, for example, to determine stability, buoyancy, and response to external forces such as water currents. Therefore, in high waves, a large pontoon moment is obtained so, so that the ship does not oscillate and remains stable moving the pendulum.

Research on using ocean waves as a source of electrical energy using a four-pendulum pontoon has strong relevance to the STEM learning approach because it comprehensively integrates concepts from science, technology, engineering, and mathematics into a project oriented toward solving real-world problems in the field of renewable energy (Mart'in -Páez et al., 2019). This relevance is represented in Figure 7.

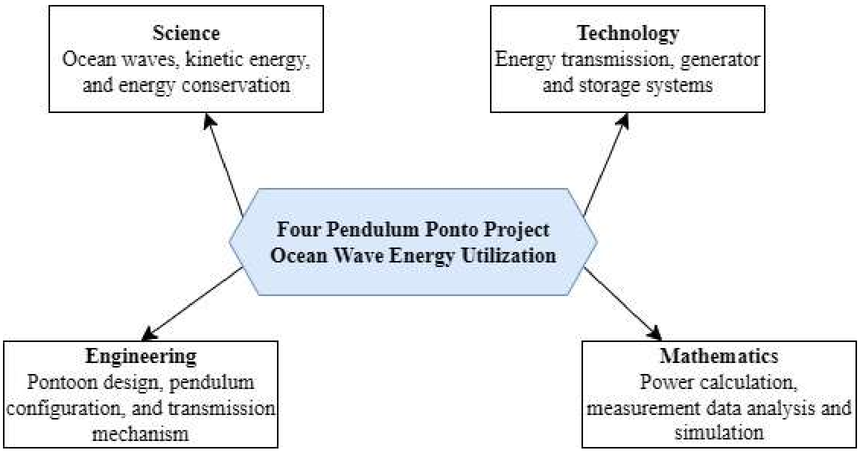

Figure 7. Relevance between the utilization of ocean waves as a source of electrical energy using four pendulum pontoons with a STEM learning approach

From the scientific aspect, this research examines in depth the principles of ocean wave physics, fluid dynamics, kinetic energy, and the process of converting mechanical energy into electrical energy, including the influence of variables such as wave height, pendulum swing angle, torque, and moment of force on electrical output. From the technological side, this study reviews the application of the Double Free Wheel Rotation transmission system, flywheel, and three-phase generator, as well as the integration of electrical technology including energy storage, AC-DC current conversion, and distribution through medium and low voltage networks. The engineering aspect is reflected through the process of designing a pontoon structure that has high stability, optimal buoyancy, and resistance to wave forces, accompanied by optimization of the pendulum configuration and transmission mechanism to increase energy conversion efficiency (Main et al., 2018). Meanwhile, the mathematical aspect is applied in the calculation of electrical power using equation (1), data processing of current, voltage, and rotation per minute measurement results, as well as analysis of the results of pontoon movement simulations and moment of force. The integration of these four aspects not only strengthens the contribution of this research to the development of sustainable marine energy technology, but also makes it an effective project-based learning model for developing 21st-century skills, such as critical thinking, creativity, collaboration, and technological literacy in students. This STEM element also encourages holistic learning, where students not only understand the theory but also apply it in the form of functional prototypes (Glosson, 2021) . Group discussions revealed that the combination of a four-pendulum pontoon design and a theoretical understanding of ocean waves resulted in improved energy conversion efficiency compared to a simpler design.

CONCLUSION

In conclusion, the wind farm experiment highlights the crucial role of the pontoon in providing stability and buoyancy, essential for standing ocean waves. Equipped with a dual free-wheel rotational transmission system, flywheel, and generator, the system efficiently converts seawater movement into electricity. Utilizing a 3-phase AC slow rotation type generator, the setup demonstrates potential for practical application. However, manual trials revealed limitations in rotation speed, indicating room for improvement. Further research should focus on enhancing pontoon design and energy conversion efficiency to maximize output. The study underscores the significance of pontoon moments in structural analysis and the need for continued innovation in wave energy technology.

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AUTHOR CONTRIBUTIONS

Daniya Nabila Bayuputri: Conceptualization, Methodology, and Writing-Review Editing; **Intan Safinah**: Methodology and Formal Analysis; **Putri Citra Ratna Gumilang**: Conceptualization and Resources; **Nadita Vera Valiska**: Methodology, Data Curation, and Formal Analysis; **Rosyidatul Mufida**: Conceptualization, Methodology, and Writing-Review & Editing; **Nurita Apridiana Lestari**: Supervision, Writing - Review & Editing; and **Muhammad Nur Huda**: Supervision, Writing - Review & Editing. All authors have read and approved the final version of this manuscript.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no financial conflicts of interest or personal relationships that could have influenced the results reported in this manuscript.

DECLARATION OF ETHICS

The authors declare that the research and writing of this manuscript have complied with ethical standards for research and publication, are in accordance with scientific principles, and are free from plagiarism.

DECLARATION OF ASSISTIVE TECHNOLOGIES IN THE WRITING PROCESS

The authors declare that Generative Artificial Intelligence and other assistive technologies were not used extensively in the research and writing of this manuscript. Specifically, an AI chatbot was used to simplify information; Neural Machine Translation (MNT) to translate the manuscript into English; and Natural Language Processing (NLP) to understand sentence structure, word meaning, and context. The authors have reviewed and edited all AI-generated content to ensure accuracy, completeness, and adherence to ethical and scientific standards, and take full responsibility for the final version of the manuscript.

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